DOCUMENT RESUME

ED 481 573 HE 036 210

AUTHOR	Breslow, Ronald
TITLE	The Doctorate in Chemistry. Carnegie Essays on the Doctorate: Chemistry.
INSTITUTION	Carnegie Foundation for the Advancement of Teaching, Princeton, NJ.
PUB DATE	2003-00-00
NOTE	17p.; For related documents, see HE 036 204-209.
AVAILABLE FROM	Carnegie Foundation for the Advancement of Teaching, 51 Vista Lane, Stanford, CA 94305. Tel: 650-566-5107; Fax: 650-326-0278; e-mail: CID@carnegiefoundation.org; Web site: http://www.carnegiefoundation.org/ cid.
PUB TYPE	Reports - Descriptive (141)
EDRS PRICE	EDRS Price MF01 Plus Postage. PC Not Available from EDRS
DESCRIPTORS	*Chemistry; *Doctoral Programs; Educational Needs; *Educational Objectives; Educational Planning

ABSTRACT

The Carnegie Foundation commissioned a collection of essays as part of the Carnegie Initiative on the Doctorate (CID). Essays and essayists represent six disciplines that are part of the CID: chemistry, education, English, history, mathematics, and neuroscience. Intended to engender conversation about the conceptual foundation of doctoral education, the essays are intended as a starting point and not the last word in disciplinary discussions. This essay reviews current practice in chemistry doctoral education and offers recommendations for structural and procedural changes in programs. Discussed in detail are the development of breadth of knowledge, depth of knowledge, and professional skills. (EV)

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ED 481 573

CARNEGIE ESSAYS ON THE DOCTORATE

CHEMISTRY

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THE DOCTORATE IN CHEMISTRY

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In March 2003, the National Research Council (NRC) will release one of its periodic surveys of the fields of chemistry and chemical engineering: *Beyond the Molecular Frontier – Challenges for Chemistry and Chemical Engineering*. The survey was created by a committee headed by Ronald Breslow, representing chemistry, and Matthew Tirrell, representing chemical engineering. In this volume, chemists in industry and academia will find many, many pages describing research that needs to be done immediately and well into the future. Each chapter lists challenges in specific areas. A list of "Grand Challenges" for chemists and chemical engineers, reproduced below, covers the entire broad field:

- *Learn how to synthesize and manufacture any new substance that can have scientific or practical interest, using compact synthetic schemes and processes with high selectivity for the desired product, and with low energy consumption and benign environmental effects in the process.* This goal will require continuing progress in the development of new methods for synthesis and manufacturing. Human welfare will continue to benefit from new substances, including medicines and specialized materials.
- *Develop new materials and measurement devices that will protect citizens against terrorism, accident, crime, and disease, in part by detecting and identifying dangerous substances and organisms using methods with high sensitivity and selectivity.* Rapid and reliable detection of dangerous disease organisms, highly toxic chemicals, and concealed explosives (including those in land mines), is the first important step in responding to threats. The next important step for chemists and chemical engineers will be to devise methods to deal with such threats, including those involved in terrorist or military attacks.
- *Understand and control how molecules react – over all time scales and the full range of molecular size.* This fundamental understanding will let us design new reactions and manufacturing processes and will provide fundamental insights into the science of chemistry. Major advances that will contribute to this goal over the next decades include: the predictive computational modeling of molecular motions using large-scale parallel processing arrays; the ability to investigate and manipulate individual molecules, not just collections of molecules; and the generation of ultrafast electron pulses and optical pulses down to x-ray wavelengths, to observe molecular structures during chemical reactions. This is but one area in which increased understanding will lead to a greater ability to improve the practical applications of the chemical sciences.
- *Learn how to design and produce new substances, materials, and molecular devices with properties that can be predicted, tailored, and tuned before production.* This ability would greatly streamline the search for new useful substances, avoiding considerable trial and error. Recent and projected advances in chemical theory and computation should make this possible.
- *Understand the chemistry of living systems in detail.* Understand how various different proteins and nucleic acids and small biological molecules assemble into chemically defined functional complexes, and indeed understand all the complex chemical interactions among the various components of living cells. Explaining the processes of life in chemical terms is one of the great challenges continuing into the future, and the chemistry behind thought and memory is an especially exciting challenge. This is an area in which great progress has been made, as biology increasingly becomes a chemical science (and chemistry increasingly becomes a life science.)

- *Develop medicines and therapies that can cure currently untreatable diseases.* In spite of the great progress that has been made in the invention of new medicines by chemists, and new materials and delivery vehicles by engineers, the challenges in these directions are vast. New medicines to deal with cancer, viral diseases, and many other maladies will enormously improve human welfare.
- *Develop self-assembly as a useful approach to the synthesis and manufacturing of complex systems and materials.* Mixtures of properly designed chemical components can organize themselves into complex assemblies with structures from the nanoscale to the macroscale, in a fashion similar to biological assembly. Taking this methodology from the laboratory experimentation to the practical manufacturing arena could revolutionize chemical processing.
- *Understand the complex chemistry of the earth, including land, sea, atmosphere, and biosphere, so we can maintain its livability.* This is a fundamental challenge to the natural science of our field, and it is key to helping design policies that will prevent environmental degradation. In addition, chemical scientists will use this understanding to create new methods to deal with pollution and other threats to our earth.
- *Develop unlimited and inexpensive energy (with new ways of energy generation, storage, and transportation) to pave the way to a truly sustainable future.* Our current ways of generating and using energy consume limited resources and produce environmental problems. There are very exciting prospects for fuel cells to permit an economy based on hydrogen rather than fossil fuels, ways to harness the energy of sunlight for our use, and superconductors that will permit efficient energy distribution.
- Design and develop self-optimizing chemical systems. Building on the approach that allows optimization of biological systems through evolution, this would let a system produce the optimal new substance, and produce it as a single product rather than as a mixture from which the desired component must be isolated and identified. Self-optimizing systems would allow visionary chemical scientists to use this approach to make new medicines, catalysts, and other important chemical products—in part by combining new approaches to informatics with rapid experimental screening methods.
- *Revolutionize the design of chemical processes to make them safe, compact, flexible, energy efficient, environmentally benign, and conducive to the rapid commercialization of new products.* This points to the major goal of modern chemical engineering, in which many new factors are important for an optimal manufacturing process. Great progress has been made in developing Green Chemistry, but more is needed as we continue to meet human needs with the production of important chemical products using processes that are completely harmless to the earth and its inhabitants.
- *Communicate effectively to the general public the contributions that chemistry and chemical engineering make to society.* Chemists and chemical engineers need to learn how to communicate effectively to the general public—both through the media and directly—to explain what chemists and chemical engineers do and to convey the goals and achievements of the chemical sciences in pursuit of a better world.
- *Attract the best and the brightest young students into the chemical sciences, to help meet these challenges.* They can contribute to critical human needs while following exciting careers, working on and beyond the molecular frontier.

Of course, these challenges are not exclusive, and no one will be surprised if chemists and chemical engineers come up with exciting discoveries that are not presaged in the survey report. But the survey challenge lists form the current "to-do" list for the field.

The NRC challenge lists also give us a window on the profession: in looking at the work ahead, one can imagine the sort of chemists who could actually carry it out. These chemists must have knowledge that is sufficiently both broad and deep so that they can cross boundaries within the field of chemistry and among the fields of science. As the list of challenges indicates, chemists and chemical engineers of the future must be able work on the interfaces of their fields with other areas such as biology, medicine, solid state physics, and environmental science.

If these are the chemists we need now, and if we will need even more of them in the future, how must doctoral education in chemistry be structured? What is the right mix of time and experience that would produce chemists, whether they are in industry or academia (or both), who can easily cross boundaries to work in and develop new fields?

These questions are not new to the profession. For example, in November 1995, representatives from industry and graduate chemistry programs met to discuss the future of U.S. doctoral education in chemistry. They were, as I later reported in *Chemical and Engineering News*, in remarkable agreement about what a doctoral education in chemistry should accomplish: mastery of a specific area within chemistry and a broad knowledge of chemistry and related fields; strong communication skills; and a sound understanding of the ethics and good practice of the profession.

Are our current doctoral programs organized to produce such chemists? In 1996, the American Chemical Society's Committee on Professional Training conducted a survey of doctoral programs. The findings pinpoint the areas in most need of change to meet this goal and suggest that we can make much better use of existing practices. In this essay, I will review current practice in doctoral education and offer recommendations for structural and procedural changes in our programs that would yield chemists with the substantive knowledge and professional skills that the future demands.

None of my recommendations would extend the time to a Ph.D. degree in chemistry—which should not exceed five years. They are designed to make better use of those five years.

The Range of Chemistry. To appreciate the need for chemists with the breadth and depth necessary to cross boundaries within chemistry itself and also among fields of science (as well as other fields), we need first to consider the range of chemistry and the way academic departments are organized.

Typically, academic chemistry departments are made up of subfields: organic chemistry, physical chemistry, theoretical chemistry, inorganic chemistry, and, in some departments, biological chemistry, and analytical chemistry (although the last two are not represented in all departments). Within these subfields there are further divisions. For example, organic chemistry includes synthetic methodology development, physical organic chemistry that is focused on understanding how reactions occur and on structure/reactivity relationships, bioorganic chemistry, natural compound isolation and identification, and many other areas. Some organic chemists also work in the field of medicinal chemistry. The other subfields of chemistry also

have their own subdivisions, such as physical chemistry concerned with gas-phase reactions, physical chemistry focused on spectroscopy, and biophysical chemistry.

Furthermore, there are many fields so close that they may well be considered part of chemistry. For example, some fundamental chemical research is done in chemical engineering departments as well as in chemistry departments. Similarly, the field of biochemistry is really part of chemistry, although it is often taught in a separate department. In the same way, medicinal chemistry is often taught in special departments in medical schools or pharmacy schools. The ACS Directory of Graduate Research lists all these departments—and also departments of clinical chemistry, polymer science, food science, toxicology, marine science, forensic science, materials science, and environmental science—as places where graduate work in some aspects of chemistry is undertaken.

Knowledge and Understanding. The two fundamental aspects of our work in chemistry—substances and transformations—also have bearing on how we educate future chemists.

Chemists want to understand the structures and properties of every substance that already exists in nature. In the earliest days there was a strong focus on separating pure chemical substances from natural mixtures, and on determining the exact chemical structure of each of the substances so isolated. This led to the identification of all the natural amino acids, for instance, as well as vitamins and sugars. Such work is still underway to some extent. For example, the structures of many proteins have been determined, usually by x-ray crystallography, but there are many more yet undetermined. The sequencing of the genomes of various species including humans involves the determination of their chemical structures, and increasingly chemists are determining the chemical structures of multimolecular systems such as the photosynthetic reaction center or the ribosome. The question is not just what molecules make up these systems, but also how those molecules are arranged.

Chemists want to create new unnatural molecules as well, not just explore nature. In fact, well over 90% of all known chemical substances have been created by chemists, not found in nature. The purpose of this work is partly to explore what is possible, but many of these created substances are also very useful. Most modern medicines, for instance, as well as pesticides, herbicides, plastics, synthetic fibers—all are the product of the creativity of chemists. After they are made their properties are examined, including biological properties, to see if they can be useful. The modern pharmaceutical and chemical industries are the result of such explorations into the unknown.

The other fundamental aspect of chemistry is transformations, what chemists call reactions. These are processes in which chemical substances are transformed into other ones, and they also have both a natural and a created aspect. Natural transformations include all the biochemical reactions in which food is transformed into proteins and fats, for instance, as well as those that produce the molecules whose energy can be used to drive muscle contraction and other vital processes. Another example is the conversion of carbon dioxide and water into carbohydrates in green plants, using light energy in photosynthesis.

Again, the new transformations invented by chemists greatly outnumber the natural biological processes, and the invented transformations are what make the creation of novel molecules possible.

Some significant part of chemistry involves the continued creation of new molecules and new transformations, in a field generally called synthetic chemistry. To put this in perspective, it has been estimated that at least 10^{40} molecules can exist made up of the common elements found in most medicines, and with about the size of a typical medicine. Some estimates are even larger. Since only a million or so molecules are now made and registered with Chemical Abstracts in a typical year, there is still plenty to do in the synthesis of new molecules. Many chemists are engaged in such synthetic efforts, and in devising the novel transformations that will make synthesis possible.

Chemistry also involves understanding. How are the structures of molecules related to their properties? How, in detail, do chemical reactions occur; which atoms move where, and when do they move? How is chemical energy used to achieve a transformation? How do other substances catalyze the reactions? Chemists working in this area can be divided into two classes: those who perform experiments to determine structure and property relationships, or reaction pathways, and those who use theoretical methods to predict properties and pathways.

Advances in techniques have made many things possible that could not be done previously. For one, advances in x-ray crystallographic methods and in other spectroscopic methods such as NMR have made it possible to determine the chemical structures of increasingly large molecules and organized systems. For another, advances in computer power and better computational programs have made it possible to predict chemical properties and reaction pathways with much better accuracy. Furthermore, new spectroscopic techniques using lasers have made it possible to measure reactions so rapidly that intermediate structures can be detected that were only matters of speculation previously.

As the "Grand Challenges" suggest, the scope of chemistry has also widened enormously. Chemists are engaged in exciting research on the borders of classical chemistry with other fields, and we see much less concern with working simply within the classical sub-disciplines of chemistry. Chemistry and the environment, chemistry and nanoscience, chemistry and molecular genetics—these are areas in which many of the most promising young research chemists are now making their mark.

Implications for doctoral education. What do the scope of the discipline and the nature of work in chemistry suggest about how we might improve doctoral education? Our Ph.D. students must learn that narrowness in education or interest is not an asset. Departments must be open to the new directions in which chemistry is moving, and they must reassess where the classical division of chemistry departments causes a problem. (Are there barriers to hiring faculty whose interests do not fit within one of the classical divisions? Are the courses as taught sufficiently refocused on the new areas in which modern chemistry is moving? Are the texts and other teaching materials suitable for chemistry as it is developing?) The negative effects of divisional structure within departments can be minimized. For example, departments can regularly hold departmental colloquia with visiting speakers who are told that they will be speaking to a general chemical audience, not just to specialists in their subfields.

Our students may well find that their future careers bring them into close contact with chemistry's sister fields. Therefore, members of regular chemistry departments should forge connections with these departments, in particular, medicinal chemistry, chemical engineering, polymer chemistry, materials science, and environmental science.

DEVELOPING BREADTH OF KNOWLEDGE IN PH.D. CHEMISTS

Ph.D.'s in chemistry should have educational breadth that covers chemistry and related fields. What does this mean? The students should have a sense of the ways knowledge can be applied in other areas. They should be familiar with experts and literature outside their own sub-discipline. As they extend their thinking about science, they will continue to grow intellectually.

How can we develop this sort of breadth in graduate students and prepare them for careers that may take them in many directions?

First, let us consider our graduate students' starting point as they enter our programs. Typically, students are admitted into graduate programs in chemistry only if they have a strong undergraduate education in chemistry. This would include at least three years of chemistry, as well as courses in physics and mathematics. The ACS Committee on Professional Training certifies the undergraduate programs of all U.S. chemistry departments on a regular basis; it also tracks the practices of graduate programs. In particular, the committee examines whether training and education has sufficient breadth among areas of chemistry, so that students do not end up narrowly educated in one of the subfields, or even one aspect of one of the subfields. Recently, the committee has listed some undergraduate education in biochemistry as a necessary component of an undergraduate major in chemistry, in addition to organic, inorganic, physical, and some analytical chemistry. Thus, graduate students who have attended U.S. undergraduate institutions should arrive with a reasonable breadth of chemical education.

A significant fraction of Ph.D. students in U.S. graduate schools come from other countries, with different educational systems. In general, they will have had even more intensive education in chemistry, with undergraduate degrees almost entirely focused on science in general and chemistry in particular. These students are usually even better prepared for our Ph.D. programs, especially if their English language skills are sufficient.

Usually students take placement exams at the start of their programs so that their departments can identify any deficiencies in preparation. Some institutions ask students to audit courses or complete a set of readings and then test them to assure mastery of elementary material. We must not produce Ph.D. chemists unskilled in the basics of our field.

Courses. How we organize the students' coursework affects the breadth of their understanding of the field. Given our students' general level of preparation, the graduate program should start with a full year of advanced course work. In most chemistry departments this would include advanced courses in the sub-specialty of the student—e.g., quantum mechanics, or synthetic chemistry methodology—along with one or two courses outside the student's specialty, for breadth. The 1996 survey indicated that, surprisingly, some departments with otherwise excellent reputations have minimal course requirements and make no demand that students do some work outside their sub-discipline. Many chemists feel, however, that such a lack of requirements produces students with an undesirably narrow education. Requiring even one third of the advanced course work to be outside the student's general area of research (for example, physical chemists taking courses outside that area) would lead to more breadth.

Also, advanced courses need not occupy an entire semester or quarter. As revealed in the 1996 survey, several departments are experimenting with modular courses, each module extending over half a term or less. The goal of educational breadth might be well served if early modules

deal with the basics, suitable for non-specialists, and later modules focus on the knowledge needed to develop experts.

As an improvement in Ph.D. programs, I would urge that every department have some requirements about courses that broaden students' understanding of chemistry. In particular, departments should offer a course in quantum mechanics designed for students whose major interest is not physical chemistry, and who are therefore less comfortable with heavy mathematics than are the physical and theoretical chemists. Similarly, departments should offer a course beyond elementary organic and inorganic chemistry, including related biochemistry, for students whose major interests are physical or theoretical chemistry. Students in organic chemistry and inorganic chemistry should also take a course in chemically sophisticated biochemistry with some medicinal aspects. They can learn much from such courses, and, indeed, many of them will end up pursuing careers in medicinal chemistry or biochemistry.

Generally, after their first year students are immersed in research. However, there is still room in their lives for advanced specialized material or courses outside the chemistry department, perhaps at a rate of one course at a time. Students should be able to audit these courses. By allowing students to audit courses outside their special area, the department would be encouraging breadth yet would keep the students' load manageable so that they can meet their research obligations.

I also recommend making minicourses or seminars available for students to attend, if not to enroll for credit, after their first year. Audited courses can broaden education without taking too much time from research.

Seminars, lectures, and colloquia. The chemistry department's seminars, lectures, and colloquia with outside speakers afford another opportunity to broaden and deepen students' knowledge. Of course, the department must offer a regular series of these events. Students should attend as many of these department seminars, lectures, and colloquia as possible, not just those in their special area. The students should be made aware that attending these programs will help them understand the range of the field (and, as I discuss below, attending these events will also help them deal with exams and research proposals).

In many chemistry departments, the graduate students themselves have the right and responsibility to invite one or more of the outside lecturers. This stimulates them to follow the scientific literature to see who and what is exciting, and student interaction with the visiting speaker helps them mature as scientists. Even with outside lecturers invited by faculty, not students, it is important that Ph.D. students have a real opportunity to speak with the visitors and discuss their own work.

Departments should invite some of their speakers from industry so that their students learn about non-academic research. Close connections between university departments and industry can also help students plan and launch industrial careers.

In any case, the outside speakers should be told that they will be speaking to an audience with broad interests and asked to introduce the topic, not just plunge right in.

Most important, the chemistry faculty should attend these seminars and colloquia, including those outside their immediate field of interest. They should attend the presentations by outside speakers, departmental colleagues, current students, and postdocs. Their presence makes clear to students the value of these events and that narrowness of interest is not a virtue in the field of chemistry.

Exams. The exams we use to measure our students' progress offer an opportunity to help them acquire the breadth they need. The one-time qualifying, or candidacy, exam used to test the advanced knowledge of the students a year or so after they enter does not stimulate students to pursue further knowledge (for example, by attending lectures or taking minicourses) after they pass. However, the practice used by some departments—giving cumulative exams six or so times a year in the various fields of chemistry—does encourage further study. These exams could include topics and material described in recent lectures (students can be notified ahead of time that a cumulative exam will be based on one of the next three outside lectures). A cumulative exam system is one way to encourage students to continue their broad education after their formal course work is done.

Interdisciplinary research. Many of the most exciting research opportunities in chemistry can be found on the borders with biology, physics, material science, medicine, and chemical engineering. Ph.D.s who will work in industry (two-thirds of the 160,000 members of the American Chemical Society are, in fact, employed in chemically-related industry) will find it necessary to work in teams with other scientists. They will have a great advantage if they have already done so as part of their graduate work. Thus, in the ideal Ph.D. program in chemistry, some of the research would be interdisciplinary and would involve collaboration with scientists outside the special field of the principal research sponsor. Students would learn to appreciate the expertise of scientists in other fields, while developing self-confidence as they see how their own expertise is valued by others.

I encourage all chemistry departments to emphasize the idea that Ph.D. research should be done, if possible, on an interdisciplinary project with more than one supervisor. This will add much to the education of the students, while preparing them for a future in which they are likely to need to work on an interdisciplinary basis.

DEVELOPING DEPTH OF KNOWLEDGE IN PH.D. CHEMISTS

Students should leave our doctoral programs with mastery of a specific area of chemistry so that they can perform successfully as true professionals. Their extensive involvement in research, leading to a thesis, is the means to this mastery.

The doctoral research. In chemistry, as in other fields, the core of the Ph.D. program is research. Generally a student joins the research group of a faculty member, and pursues a research problem that is suggested by the mentor. Also, the mentor monitors progress and makes suggestions throughout the course of the program. The intensity of such monitoring varies, from "What did you do yesterday, and what are you going to do today?" to "Please let me know if you run into any problems, or make any important observations." Some students, especially at the beginning, benefit from close supervision, while others learn more if they are left, to some extent, on their own.

It is quite unusual for students to propose and carry out their own research ideas, unrelated to the interests of the faculty mentor. Generally, it is a goal of the Ph.D. program to bring students to the point at which they could, indeed, propose a sensible research problem. However, it is expected that students will read the background and current progress in their field, and will make useful suggestions that can alter the course of the research project. As the project progresses, supervision usually becomes looser and looser.

A successful Ph.D. research project normally leads to scientific publication, and students are usually asked to write at least the first draft of a paper reporting the work. As a rule, the faculty mentor would be a coauthor, recognizing his role in initiating the project and in guiding it. Thus, the final draft of a paper is the responsibility of the faculty mentor.

Research in chemistry generally receives financial support from funding agencies, with grants to the faculty mentor. The Ph.D. students are supported financially from the funds that support the project on which they are engaged. In addition, some students can win independent fellowships, or become part of a general training grant awarded to the department.

Stimulating creativity. One of the marks of an educated Ph.D. chemist is the ability to propose good research projects. The projects should have the following characteristics: 1) they should be novel, and not just trivial extensions of previous work; 2) they should have a reasonable chance of being successful, either achieving a pre-determined goal or likely to produce new information in an interesting area; 3) they should be important enough that the student would be proud to publish the work, if successful, in a leading journal; 4) ideally, they should have a reasonable chance of opening up a new field or area of research. In proposing such a project, students should be able to indicate not just the goals of the work but also how they will be approached. Students should be able to describe possible problems that can arise in the course of the work, and how those problems will be solved.

As I noted above, one of the goals of a Ph.D. program in chemistry is to enable students to reach a maturity that will let them propose good research ideas and programs. Students who hope to obtain an academic position in chemistry will be expected to propose three to five research ideas that they will pursue if they are hired, while even students who will not be entering an independent research career will benefit from having learned how to propose research ideas. For example, those Ph.D.s working in a pharmaceutical company are expected to be able to propose new goals and procedures if they are to progress in the company.

How might departments make better use of the students' research experience so that they have sufficiently deep mastery of their areas and are also encouraged to think creatively about research?

Research proposals. Original research proposals, defended orally, play an important role in both deepening students' mastery and extending their broad knowledge. They also prepare students for the future in practical ways. Preparing a research proposal involves reading the chemical literature, a habit that is the hallmark of a professional. Students who hope to win postdoctoral fellowships will need to make such proposals as part of their applications. Students who hope to obtain academic positions will need to have a group of such proposals ready as part of their job applications. Those seeking positions in industry will find that research proposals are used as an indicator of the candidate's creativity.

All chemistry departments should require students to propose one or more research ideas as part of their education. One proposal might be closely related to the thesis research; it could, for example, elaborate on the ways the research can be extended. Another research proposal could be on a topic different from that which the student is researching. The students should be required to submit a written version of each proposal, with adequate references, and to defend their proposal(s) before a faculty committee. To preserve the intellectual property of the students, these proposals would not normally be presented in an open public meeting.

Many chemistry departments already require that students to submit and defend one or more research proposal as part of their program. For practical reasons, it is expected that these proposals will not be very close to the research project that the student, or another student in the department, is pursuing. In a few departments, students actually fill out dummy NIH research proposals to be graded: in this exercise, they learn not only how to present an idea but also how to estimate and justify the cost of pursuing it.

Lectures, journals, and exams. When students know they are expected to propose research ideas of their own, they will listen to lectures by departmental and outside speakers and read papers in the major journals with the question in mind: "Is there something here that can stimulate a research idea of my own?" A system of regular cumulative exams based on recent important advances reported in the research literature will also keep students thinking about possible research projects related to recent advances in research.

The thesis. Every Ph.D. student is required to submit a final thesis. Normally this is an extensive written document, with a history of the problem, a description of the results obtained, and an experimental section describing how the work was performed. It usually describes not just the positive findings that led to publishable work, but also the other efforts that did not or would not make it into a scientific publication. It is thus a more valuable document that a mere collection of published papers, since those who follow the work need to see the downs as well as the ups in the field. Also, a thesis is normally the product of the candidate him- or herself, while papers have many authors. Thus, I urge departments to consider the value of a written thesis over a collection of reprints or preprints.

The faculty should carefully mentor their students through the thesis process. For example, early in the process, each student should have a thesis committee. The committee members should hear and critique the student's presentations (e.g., public seminars), read and respond to research proposals, monitor research progress, and participate in any special examinations. The members should be part of the final dissertation committee, and they should be prepared to serve as important references in the student's job search.

Thesis directors have special responsibilities. They must follow the progress of the student's research and give sound advice. They should coach the students as they develop their speaking and writing skills. They should preview and critique the talk that students will give during job interviews. Finally, all faculty mentors should recognize the variety of rewarding and meaningful careers paths that Ph.D. chemists can follow: they should support and encourage the student's career decisions, whether traditional or non-traditional.

Typically, there is an exam as part of the thesis defense. That is, the thesis committee will ask the student questions not only about the details of the thesis but also about advanced level

material in the general field. For example, a student with a thesis on NMR spectroscopy will be expected to be able to explain ESR spectroscopy. A student with a thesis on various synthetic reactions will be expected to know how those reactions occur in molecular detail, or perhaps to know how the same transformations are performed biochemically.

Requiring an examination with the thesis defense offers another opportunity for departments to encourage deep mastery of an area. Departments should institute this requirement as a way to confirm the quality of the Ph.D. students, as well as their theses, and to signal expectations about deep knowledge.

Further, in departments where students are required to propose new research ideas, the examination will uncover not only how good the proposal is, but also how much the student knows about the field in which the proposal is centered.

DEVELOPING PROFESSIONAL SKILLS

In addition to broad and deep knowledge, Ph.D.'s in chemistry need professional skills: speaking and writing well, making information and ideas clear to different audiences, teaching effectively, understanding good scientific practices and ethics, and providing service to the discipline. As I suggested in describing ways the help Ph.D. students achieve breadth and depth of knowledge, graduate programs can make good use of existing structures and requirements to give their students solid skills for their professional lives.

Strong communication skills. Readers will note that among the "Grand Challenges" is a call for effective communication. Scientists need strong skills for communicating with their colleagues in science and a variety of other audiences: for example, non-science professionals, policy makers, students, and the public. The graduate years offer several opportunities for students to develop strong communication skills.

Oral and written skills. Scientists need to speak and write well. Graduate programs should make efforts to help their students to develop these skills. For example, students should deliver several public seminars, both on their research and on topics from the research literature. The exercise of planning and delivering a public seminar or lecture—even an informal one—gives the student practice describing research and conveying both the relevance and the details of the work.

Students should regularly report orally on their research progress, usually in meetings of their research group with their sponsor. These reports, although informal, are important occasions to practice speaking skills. In addition, students should give at least one talk before all the students, postdocs, and faculty in their area of interest—for example, in front of all the physical chemists or organic chemists. In preparing this talk, the student should give great attention to organization of the material and the use of visuals (overheads, slides, or, increasingly, PowerPoint).

Although students should have many opportunities to speak about their own research achievements, there is much to be said as well for giving a talk on some topic from the chemical literature that is not very close to the research of the student. These "literature" talks teach the student how to do a good literature search and how to select a topic with good general interest. The result of the talk is that the student will now have expertise in an area other than his or her

thesis topic, and this expertise can be the basis for creative research proposals. For many students, a talk based on the work of a scientist from a different university leads to an interest in doing postdoctoral work with that scientist.

Speaking at a national or regional chemistry meeting can be a particularly maturing experience. The student should have a good deal of support from the department, with detailed and helpful feedback on draft proposals and presentations and opportunities to rehearse in front of students and faculty, including practice fielding questions from the audience.

I urge that all departments give their Ph.D. students the opportunity to give at least one or two formal talks before the department or one of its subdivisions, with a written abstract and references and with visual aids. The quality should be comparable to that which the student might use later in job interviews. The faculty should make every effort to attend these talks and give students helpful critiques.

The few departments where presentations are not required (often quite distinguished departments) explain their position by arguing that listening to such talks consumes faculty time, and preparing them consumes student time better spent on research. As a result, both students and faculty miss an important opportunity for learning and teaching.

Preparing for the kind of oral presentations described above is one way to hone writing skills. Likewise, preparing research reports and research proposals offers students an opportunity to develop and sharpen writing skills. These tasks can also lay the groundwork for a well-written thesis and scientific papers. But the students can only develop and improve these skills if they receive thoughtful and timely critique from the faculty and peers.

Another important communication skill for any scientist is the ability to summarize research in ordinary language for the public. Those who are our students now will spend much of their careers trying to make their achievements comprehensible to intelligent non-scientists, such as government officials. Some will also have the responsibility of speaking about the field to the public. And some will teach. To develop this skill and emphasize its importance, a few departments now require that the thesis contain an additional section, sometimes at the back, summarizing in laymen's terms what has been accomplished in the student's research and how it is important. The section is written so that a non-expert could get a reasonable grasp of the main point of the thesis. This requirement gives students practice in explaining their work to non-chemists, indeed to non-scientists. This requirement is unusual, but should not be.

Language skills. Some ability to read foreign languages is extremely valuable. At one time, all Ph.D. students in chemistry were expected to pass one or two examinations in foreign languages, usually German and French. This requirement has largely faded away, as the scientific literature is increasingly published in English regardless of the country of origin. Now there is no language requirement in most departments, although foreign students are expected to be able to read and speak English. However, organic chemists still need to be able to read the old chemical literature, especially that written in German. For example, articles in *Chemische Berichte* and in Liebig's *Annalen* are still relevant, in which procedures are described for the synthesis of compounds that can be needed in modern research. The compendium known as *Beilstein* is still a source for the properties and preparative procedures of organic compounds.

Thus, it is by no means true that chemists have no need for some proficiency in foreign languages, even if the formal requirements are disappearing.

I urge all chemistry students planning to work in organic chemistry to attain at least the skill in reading German that lets them understand the experimental sections of papers in the leading German chemical journals of the 1930s or so, when English translations were not routinely produced.

Teaching. As the saying goes, "If you want to learn a subject, teach it." For this reason, teaching in labs and classrooms is a valuable part of graduate education. Teaching helps solidify knowledge, and teaching elementary material helps call attention to significant intellectual gaps in the field that can be subjects for future research. Teaching experience is also helpful for those who will later take up academic careers, and for those in industry it will be helpful in learning to deal with technicians, for instance. It also affords practice in explaining scientific material to non-experts.

Chemistry Ph.D. students usually do at least some undergraduate teaching as a component of their programs. In part, this is a source of financial support – teaching assistantships support many students in their first year or so of graduate study, although it is common for them to be supported from research grants or training grants or fellowships in the later years of their program. However, when other sources of support are not available, students often do part-time teaching through all the graduate years.

Graduate students report that the teaching they do is extremely valuable to their education. Thus, even when students arrive in graduate school funded by personal fellowships, such as those given by the NSF, it is not unusual for them to do some teaching for its educational value to them, not for financial support.

For graduate students in chemistry, teaching normally involves acting as teaching assistants (TAs) in laboratory courses. Additionally, the TAs will give some laboratory lectures, and may also do some subsidiary teaching of material covered in the lecture courses. It is quite unusual for graduate students themselves to have full responsibility for chemistry lecture courses, however. At most, the graduate students might run some recitation sections or exam review sessions, while the regular faculty members deliver the lectures in the courses.

I urge that some teaching experience be part of the requirements for all Ph.D. students, even those with adequate financial support from fellowships or grants. The teaching should involve some lecturing, for instance in supplementary or review sections, not just policing the lab. Laboratory supervision is useful, but the students learn more by giving laboratory lectures or running recitation and review sections. Of course, departments should make sure they their students are adequately prepared for their teaching assignments and are supervised in carrying them out.

Good scientific practice and ethics. As professionals, chemistry Ph.D.s will be expected to follow good scientific practice and act with integrity. They also need to know how to decide whether research results are correct. Many chemistry departments now offer short lecture programs devoted to discussing scientific responsibility, validating research, and the techniques that can be used to avoid serious mistakes. I urge that all beginning Ph.D. students receive at

least a few lectures on scientific responsibility and integrity. The lectures can also discuss intellectual property, patenting, and other non-scientific matters, such as proper record keeping.

Professional service. Active membership in the professional society of the discipline is an important service to the field, a habit that students can develop long before graduation. The activities of the ACS are directly concerned with carrying forward the best practices in chemistry and improving on them. For example, the publications include many of the leading journals in the field, at prices well below those of commercial competitors. There are dozens of committees concerned with every aspect of chemistry, including best practices in education. Of course, most of the members of those committees are established professionals, but great efforts are made to involve young people, even below the level of graduate students. Most colleges and universities have an ACS student chapter for undergraduates, and there are ACS publications specifically directed to them. The ACS has a Younger Chemists Committee that meets regularly and reports to the Council of the ACS at every national ACS meeting.

SUMMARY

There is much interest among U.S. chemists in the topic of improving and changing doctoral education. For example, the ACS recently established an Office of Graduate Education to promote useful change and to monitor progress. The new head of the Chemistry Division of NSF is very concerned with education in chemistry, including graduate education, and he recently participated in a symposium devoted to graduate education at a national ACS meeting. I hope that this essay will contribute to this ongoing discussion.

Chemistry is undergoing great changes in its research areas, both fundamental and applied, and our graduate programs must keep up with these changes. As I hope the preceding discussion makes clear, graduate chemistry programs could considerably strengthen the way new Ph.D.'s are prepared to work in this changing field by making better use of existing structures and adopting effective practices already used in some departments.

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